RADIATION DAMAGE EFFECTS ON HIGH-PURITY GERMANIUM DETECTORS

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The NASA-funded IUCF-LBL experimental program to study the effects of radiation damage and the subsequent annealing of high-purity germanium detectors continues. The goal of the program is to determine the effects of radiation damage on the energy resolution of germanium detectors as a function of many experimental factors such as irradiation fluence, material type (n and p), geometry (planar and coaxial), electric field, temperature, flux of ionizing radiation, annealing characteristics, and type of damaging radiation. The FWHM and FWTM of the 1332-keV gamma-ray line from a ^{60}Co source are the standard measurements of detector performance. The detectors are mounted in liquid-nitrogen cooled, variable-temperature cryostats that can maintain the detectors at stable temperatures ranging from ~84 °K to ~150 °C (423 °K). To cool detectors to slightly lower temperatures, the dewars of LN_2 were pumped by an external mechanical pump. The detectors were operated in a range 72–135 °K. All cryostats are equipped with infared shields.

In February 1992 eight planar detectors and one large coaxial detector were irradiated to various fluences of 183-MeV neutrons. Table 1 lists these irradiations, including material type and fluence. Cryostats 1, 2, 3, and 4 are dual detector systems that contain 1-cm thick planar detectors having diameters ranging from 20 to 30 mm. The cryostat labeled COAX-1 contains Solar 2, a 6.7-cm diameter coaxial detector 6.8-cm long.

Table 1. FEBRUARY 1992 NEUTRON IRRADIATION

CRYOSTAT	DETECTORS		FLUENCE
1	644-1.5 (p)	691-15.7 (n)	7.2×10^8 n/cm^2
2	486-2.3 (p)	689-4.9 (n)	7.4×10^7 n/cm^2
3	508-3.9 (p)	311-1.2 (n)	1.5×10^8 n/cm^2
4	475-3.0 (p)	691-13.1 (n,p)	3.2×10^8 n/cm^2
Coax-1	Solar 2 (n)		3.2×10^8 n/cm^2

The neutron beam was created by 200-MeV protons incident on a liquid deuterium target in the IUCF polarized neutron facility. All detector systems were irradiated at

LN_2 temperature and not allowed to warm up to room temperature until the full low-temperature resolution vs. temperature curve was determined.

The basic plan was to measure resolution as a function of temperature at and above LN_2 temperature. In doing this, one must be careful to watch for bias-induced degradation of resolution that can occur over long periods of time. After the bias is applied to a damaged detector, the resolution may continue to change for the order of 2–3 days. This effect is very sensitive to temperature and fluence. For example, when maintained at 103 °K, the resolution of the p-type detector in cryostat 4 degraded from FWHM = 4.0 keV on the first day bias was applied, to 5.0 keV the following day, and to 5.5 keV the third day; from then on the resolution remained fairly constant. The same effect is relatively small at LN_2 temperatures. These measurements were done with a constant source strength of gamma rays incident on the detector. This effect is larger for detectors irradiated to a higher fluence.

The strength of the ^{60}Co source itself has a measurable effect on the resolution. The charge produced by the source fills up positive charge carrier trapping sites (hole traps) making them less efficient at trapping charge and therefore improving the resolution. This filling decays slowly with time, so the influence upon resolution depends upon the event rate. It is well known that positive charge carrier trapping is the main cause for resolution degradation in radiation-damaged germanium detectors. Bias-on time, source strength, and limiting amplifier pileup considerations forced us to be very careful to normalize the count-rate-per-unit-volume to a standard constant for all the detectors. The bias was left on for several days before measurements were made.

The time over which the resolution of the detector degrades to an equilibrium as well as the amount the detector degrades were both points of interest to us. For this reason, measurements were generally made as follows: place the 24-μCi source directly on the top of the cryostat cap until the resolution stabilizes at that count rate (usually about 1/2 hour), quickly replace this source strength with a 4-μCi source 3.8 cm from the top of the cap (this reduces the count rate by an order of magnitude), and measure the resolution as the performance of the detector degrades because of the lower count rate. The resolution was measured repeatedly as it degraded with time. This was done to some extent for all the detectors. We were most interested in the final equilibrium resolution because detectors are generally operated with bias on for an extended time. The final equilibrium resolution vs. temperature for Solar 2, the coaxial detector, is shown in Fig. 1. The upper curve is the FWTM, the lower is the FWHM. If one looked only at the FWHM, one would have a very different picture of how badly Solar 2 was damaged compared to the picture presented by the FWTM. From Fig. 1 one can clearly see the extremely strong dependence of detector resolution degradation on temperature, with the FWTM curve rising proportionally much faster than the data on FWHM.

Figures 2 and 3 show the analogous set of curves for the n- and p-type planar detectors in cryostats 1 and 2, respectively. Again, the top curve is FWTM and the bottom one FWHM. Cryostat 1 received the highest fluence, cryostat 2 the lowest. The detectors reflect their fluences, the detectors in cryostat 1 having a resolution worse than 4 keV about 25 °K lower than the detectors in cryostat 2. Note the p-type detector is consistently better than the n-type detector in both cryostats.

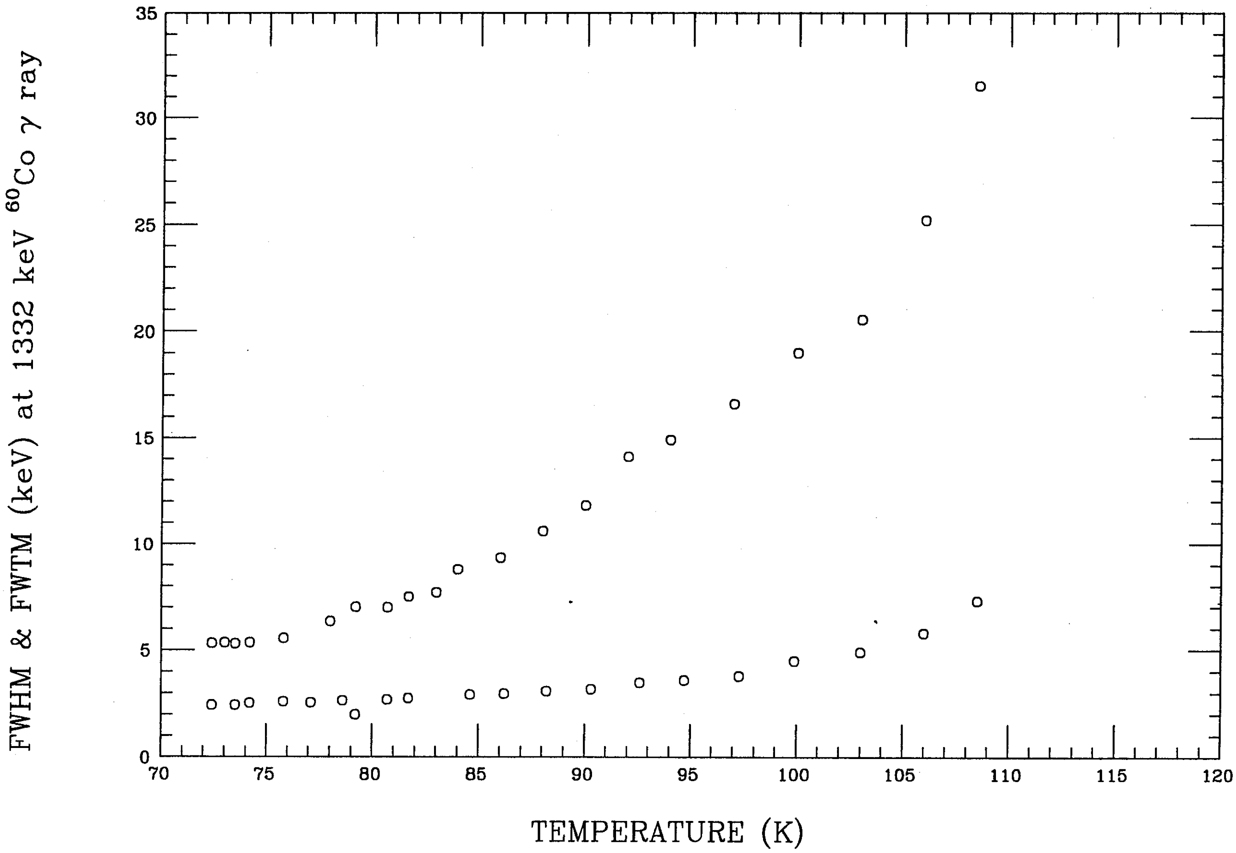

Figure 1. FWHM and FWTM of the 1332-keV γ-ray resolution for an n-type coaxial detector, Solar 2, after 3.2×10^8 n/cm^2.

The "low temperature annealing" (72–135 °K) of the detectors in cryostats 1, 2, 3, and Coax-1 all went fairly smoothly. We obtained good data from the detectors in cryostat 4 up to 103 °K. When we tried to increase the bias over the normal operating bias (2000 V), both detectors were damaged to the point that they would no longer take 2000 V bias without having extremely high leakage current and terrible resolution (FWHM = 30 keV). In an attempt to reduce the leakage current, the detectors were warmed to 120 °K with the bias off and then cooled back to LN_2 temperature. The resolution at LN_2 temperature of both detectors was then better (2.2 keV) than it had been since before the irradiation even though 2000 V bias still could not be applied. Subsequent 120 °K temperature cycles eventually resulted in 2000 V bias on one detector and 1600 V bias on the other. This provides a dramatic example of the effective cryopumping done by the infared shield surrounding the detector in the cryostat. The surfaces of the detectors apparently were cleaned up significantly.

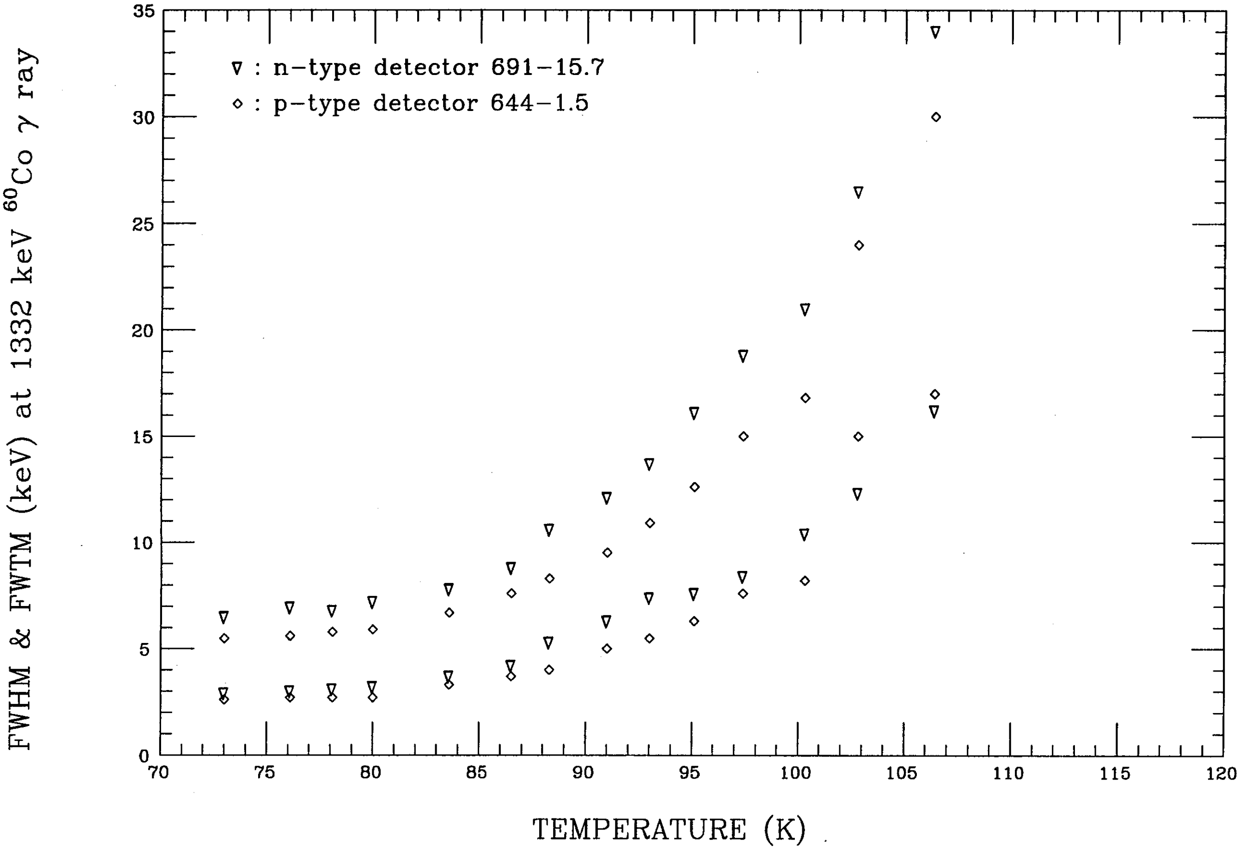

Figure 2. FWHM and FWTM of the 1332-keV γ-ray resolution for n- and p-type planar detectors in cryostat 1 after 7.2×10^8 n/cm^2.

A major goal of this experiment was to compare the effects of protons from prior experiments and neutrons from this experiment on the same set of detectors. Data from all detectors indicate that protons and neutrons of similar energy cause very similar damage characteristics in germanium detectors over the energy range studied, $\sim$130–200 MeV.

During the course of this experiment (February 1992 to March 1993) we were motivated to try several new and different things. There have been upgrades in the electronics and the thermal control characteristics of the cryostats as well as shielding efforts to reduce electromagnetic interference. The improvement produced by lowering the temperature of Solar 2 only a few degrees below LN_2 prompted the fabrication of a p-type coaxial detector to see if we could significantly compensate for the electrode disadvantage with a decrease in temperature.

A second neutron irradiation occurred in March 1993; the same neutron beam was used as in February 1992. For the second irradiation a total of ten planar and four coaxial detectors were irradiated. A total of eight cryostats were used. One of the coaxial detectors was irradiated at room temperature while not mounted in a cryostat. Cryostat 5

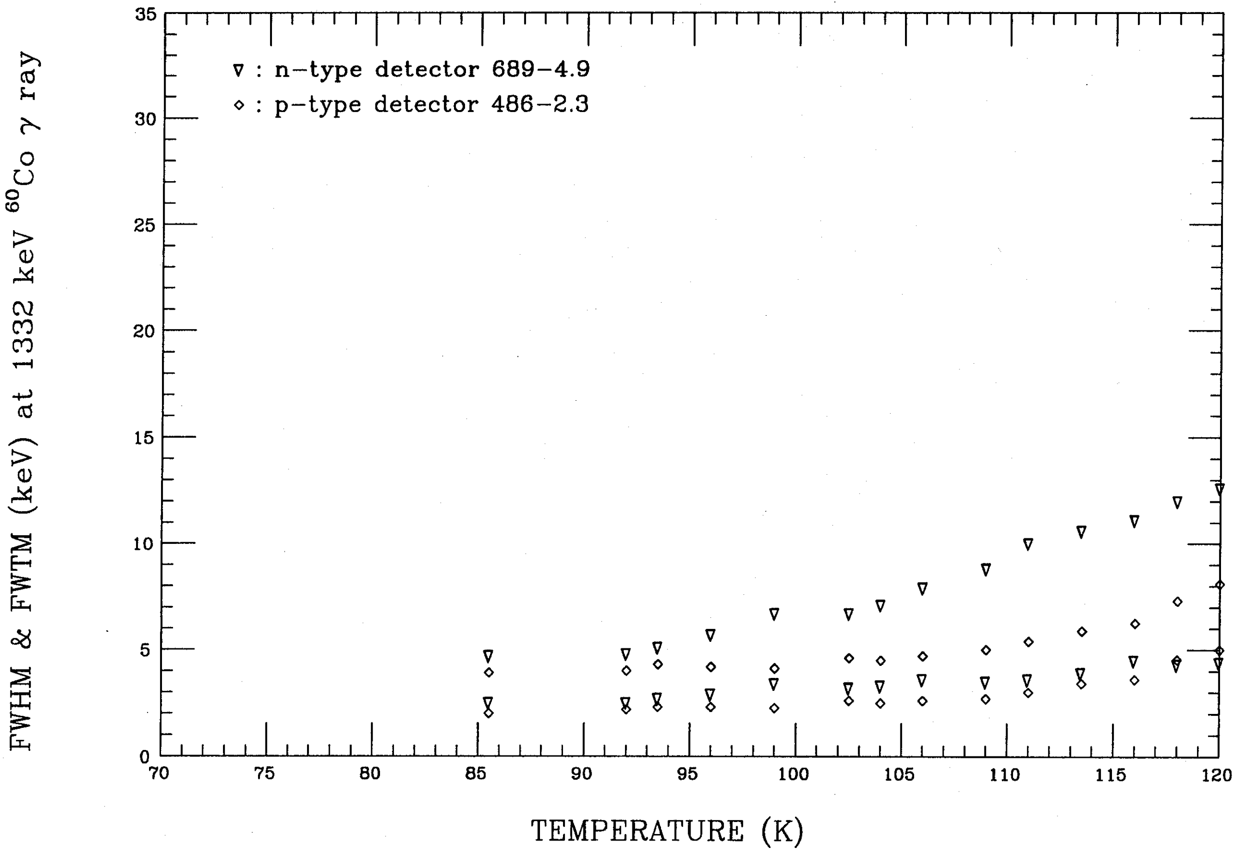

Figure 3. FWHM and FWTM of the 1332-keV γ-ray resolution for n- and p-type planar detectors in cryostat 2 after 7.4×10^7 n/cm^2.

(containing the planar detectors originally in cryostat 102), an additional n-type coaxial detector (Solar 20), a p-type coaxial detector, and the unmounted n-type coaxial detector (Solar 17) were added for this irradiation. The detectors fabricated from n-type material were irradiated with bias on and some of the planar detectors were irradiated with the electric field direction orthogonal to the beam direction (orthogonal to normal irradiation direction). Table 2 lists these irradiations, including material type, fluence, orientation and bias history. Study of these detectors is underway.

Table 2. MARCH 1993 NEUTRON IRRADIATION

CRYOSTAT	DETECTORS		FLUENCE
1 (orthogonal)	644-1.5 (p)	691-15.7* (n)	7.2×10^{8} n/cm^2
2 (orthogonal)	486-2.3 (p)	689-4.9* (n)	7.4×10^{7} n/cm^2
3 (orthogonal)	508.3.9 (p)	642-1.5 (p)	1.5×10^{8} n/cm^2
4	475-3.0 (p)	691-13.1 (n,p)	3.2×10^{8} n/cm^2
5	280-1.0 (p)	494-3.1 (p)	1.2×10^{9} n/cm^2
Coax-1	Solar 2* (n)		3.2×10^{8} n/cm^2
Coax-2	Solar 20* (n)		7.4×10^{7} n/cm^2
p-coax	p-type coax (p)		1.5×10^{8} n/cm^2
unmounted coax	Solar 17 (n)		1.2×10^{9} n/cm^2

* Bias on during and after irradiation.